FIRRE Joint Battlespace Command and Control System for Manned and Unmanned Assets (JBC2S)

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ABSTRACT

The Family of Integrated Rapid Response Equipment (FIRRE) is an advanced technology demonstration program intended to develop a family of affordable, scalable, modular, and logistically supportable unmanned systems to meet urgent operational force-protection needs and requirements worldwide. The near-term goal is to provide the best available unmanned ground systems to the warfighter in Iraq and Afghanistan. The overarching long-term goal is to develop a fully-integrated, layered force-protection system of systems for our forward deployed forces that is networked with the future force C4ISR systems architecture. The intent of the FIRRE program is to reduce manpower requirements, enhance force-protection capabilities, and reduce casualties through the use of unmanned systems. FIRRE is sponsored by the Office of the Under Secretary of Defense, Acquisitions, Technology and Logistics (OUSD AT&L), and is managed by the Product Manager, Force Protection Systems (PM-FPS), Fort Belvior, VA.

The command-and-control element of FIRRE is the Joint Battlespace Command and Control System (JBC2S) for manned and unmanned assets, which is based upon the Mobile Detection Assessment Response System (MDARS) Multiple Resource Host Architecture (MRHA), modified to operate as a single application program using standard DoD mapping and data distribution services. JBC2S is an evolution of the MRHA that leverages over 10 years of development in unmanned systems command-and-control. It implements the functionality of the MRHA under the dynamically configurable and highly modular architecture of the Multi-Robot Operator Control Unit (MOCU). JBC2S is a network-centric, geospatial command and control system that allows the field commander and above to plan and execute missions utilizing multiple and disparate manned and unmanned assets. It utilizes standard map formats (GeoTIFF, DNC, CADRG) for displaying map data and for tracking asset placement and movement.

Keywords: FIRRE, JBC2S, MOCU, MRHA, command and control, ground surveillance radar, unattended ground sensor, unmanned ground vehicle, robotic architecture, force protection

1. BACKGROUND

The purpose of FIRRE is to provide the best available force protection technologies to our forward deployed forces today, while assisting the Combat Developer in developing concepts and capabilities analysis for the future. FIRRE provides our soldiers, airmen, marines and sailors with an enhanced layered force-protection system of systems capability that provides the means to detect, assess, identify and respond to enemy intrusion activities. FIRRE enhances force protection, keeps friendly forces out of harm's way and allows commanders to return warfighers to their primary wartime missions.

The proponent for FIRRE is the U.S. Army Maneuver Support Center (MANSCEN) at Fort Leonard Wood, Missouri. Current plans call for FIRRE to participate in a July-August 2006 demonstration at Yuma Proving Ground, Arizona, and to eventually integrate with the Counter-Rocket, Artillery and Mortar (C-RAM) program as part of MANSCEN's 360-degree Comprehensive Fixed Site Protection Initiative (CFPI) concept. If successful, this integrated effort will be deployed in FY-07 to provide a force-protection capability against indirect fire and ground intruders.

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The formal requirements for the FIRRE program are being developed by MANSCEN as part of the U.S. Army Training and Doctrine Command's (TRADOC) chartered Unit Protection Concept Capability Plan (UPCCP) Integrated Concept Development Team (ICDT). The FIRRE Integrated Product Team (IPT) was charted by the OSD Joint Robotics Program (JRP) Coordinator and meets periodically as required. The IPT consists of over 60 members from 10 different agencies. Key members include PM-FPS, SSC San Diego, MANSCEN, Aberdeen Test Center, PM Robotic and Unmanned Sensors, PM Night Vision, and other members of OSD's JRP.

Over a 9 month period, the FIRRE IPT developed an "80-percent solution" that is affordable, supportable, and uses military equipment where possible, or readily available commercial equipment where practical. The resulting system has been demonstrated in two week-long field exercises at Hawthorne Army Depot in Nevada over an operational area in excess of 35 square kilometers. Portions of the FIRRE system have undergone formal environmental testing to include heat (to 120° F), blowing rain (to 40 MPH), shock and vibration, transportability, and center of gravity.

2. SYSTEM OVERVIEW

FIRRE has been designed to be deployed in a rapid fashion for tactical missions or integrated into base operations as part of a complete force-protection package. As FIRRE is a system of systems, its configuration is flexible and scalable, and the exact table of equipment for a particular application is based upon METT-T (Mission, Enemy, Troops, Terrain, and Time). Nominal deployment of FIRRE consists of a single command-and-control (C2) Station controlling multiple unmanned assets operating over an area of approximately 100 square kilometers, which approaches the physical extents of the current communications architecture. Shown in Figure 1, a conceptual FIRRE system for performing perimeter security of a moderate-sized (7 x 5 kilometer) ammunition base could consist of:

- 1 M1152 HMMWV with S-788 Shelter
- 6 Blue Sky Masts with Radio Antennas
- 1 PU-798 10KW Generator Trailer
- 2 M1102 Support Equipment Trailers
- 4 Remote Sensor Stations (RSS)
- 50 BAIS Unattended Ground Sensors (UGS)
- 2 TAGS Unmanned Ground Vehicles (UGV)

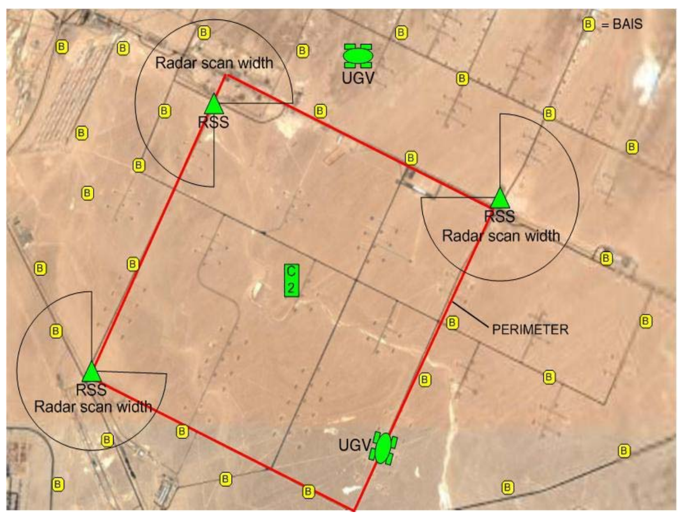

Figure 1: Conceptual deployment of the FIRRE system.

Remote Sensor Stations are emplaced around the perimeter of the site to provide wide-area detection and assessment. Unattended ground sensors are emplaced along likely avenues of approach such as roads and wadis. Multiple UGVs patrol the interior of the site as well as the perimeter to fill in gaps in the fixed sensor coverage using randomized patrol patterns. If an intruder is detected, the closest UGV will automatically be cued to assess this potential threat. This system is controlled using JBC2S which is hosted in a HMMWV-shelter based command-and-control station [2].

3. COMMAND AND CONTROL ARCHITECTURE

3.1 MRHA, MOCU, and JBC2S

The Multiple Resource Host Architecture (MRHA) was developed by SSC San Diego as the command-and-control system for the Army's Mobile Detection Assessment Response System (MDARS) program. MDARS is a fixed-site robotic security system that consists of multiple semi-autonomous unmanned ground vehicles (UGVs) performing automated patrols, as well as intrusion sensors and active barriers. The UGVs can automatically detect and track intruders and perform inventory assessment of items within buildings or bunkers using RFID tags. The MDARS program is currently undergoing extensive testing at Hawthorne Army Depot and is expected to enter limited production in early FY-07.

The Multiple-robot Operator Control Unit (MOCU) [1] was developed as a tactical operator control unit for a small man-portable UGV called the URBOT. It has since been modified to control the SPARTAN unmanned surface vehicle (USV) as well as the iRobot Packbot, and a modified Rotomotion unmanned aerial vehicle (UAV). MOCU differs from the MRHA in a number of important areas. First, MOCU is designed from the ground up to be modular and scalable. It can be run on an embedded handheld or high-end desktop computer. MOCU is designed to allow for plug-and-play modules that support new C2 protocols, video CODECs, mapping engines, and other components to be added without modifying the core software. MOCU is protocol, video, and map agnostic, which allows it to grow and adapt to support new platforms using whatever the interface de jour may be.

The MRHA, on the other hand, was developed using the Ada programming language and has become increasingly difficult to maintain. Additionally, as MDARS nears production, it has become difficult to add new features since the software has already undergone formal testing. Even though the MRHA was designed for a very similar mission to FIRRE, it was prudent to move to the newer MOCU framework to allow the use of the latest software tools and libraries, while still maintaining backward compatibility by implementing an MRHA IDD command-and-control protocol module. By adding the MRHA functionality such as automated path planning and resource scheduling and scripting to MOCU, a single software application could be created that would consolidate the code base while leveraging over 10 years of unmanned systems command and control software experience.

The MRHA uses proprietary vector graphics to depict the location of robots, sensors, roads, and bunkers. MOCU features much more advanced 2-D vector and raster graphics using map modules. There are currently map modules that support GeoTIFFs, World Vector Shoreline (WVS), Digital Nautical Charts using the COmmon GEospatial Navigation Toolkit (COGENT), and the Commercial Joint Mapping Toolkit (C/JMTK). What it is needed, however, is a 3-D mapping engine that will allow for seamless worldwide coverage, take advantage of modern graphics hardware, and provide the operator with better situational awareness. JBC2S is a fusion of the framework of MOCU, the functionality of the MRHA, and cutting edge 2-D and 3-D visualization technology (Figure 2).

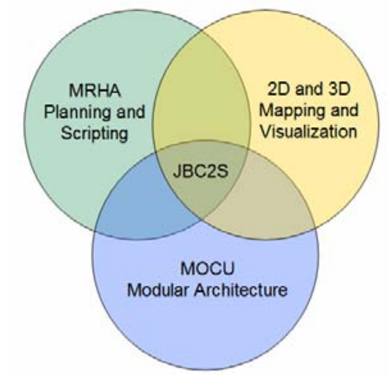

Figure 2: JBC2S architecture.

3.2 Communications

The requirements of FIRRE's mission dictated the use of high power, long range communications equipment rather than standard 802.11 wireless networks that normally used for robotic applications. Typically, when a TCP/IP network is used, both command and control and video signals are sent over the same link; however, there are currently very few TCP/IP radios capable of communicating in a mobile environment with bandwidth sufficient for good quality video and 5+ KM range. The few radios that do exist, such as the *AN/VRC-99*, are prohibitively expensive and most have embedded COMSEC encryption that makes them problematic for unmanned systems. FIRRE uses two separate radio links that provide the necessary performance while staying within budget.

Intuicom Military Navigator II (MilNavII) UHF transceivers are used for bi-directional command and control with a maximum throughput of 128kbps (full-duplex), 4W output, and a stated 60+ mile range (LOS). The *MilNavII* can be configured in point-to-point, point-to-multipoint, and repeater modes and also has a built-in WAAS capable GPS. The *MilNavII* radio provides three virtual RS-232 serial channels between two radios in point-to-point mode. The first channel is used for bi-directional command and control using a derivative of the MRHA protocol. The second channel provides one-way differential GPS correction messages from the FIRRE C2 Station to the UGV. The third channel can be used as a remote terminal into the FIRRE UGV to allow for remote debugging.

DTC Palladium COFDM transmitters and receivers are used to send a single channel of high quality NTSC video to the C2 Station. To achieve the desired range, a 12W external amplifier was added, and for non-mobile applications, a 25° 15 dB directional antenna was also employed. The receiver uses two omni-directional antennas in a spatial diversity configuration.

Both of these radio links are used in point-to-point mode. The current limit based on rack space in the C2 Station is 6 resources (any combination of FIRRE UGVs or RSS towers). Support for additional resources can be provided by connecting external radios via ethernet or adding connectors to the egress panels on the back of C2 Station.

3.3 Protocol Modules

One of the more common protocols for controlling unmanned vehicles is the Joint Architecture for Unmanned Systems (JAUS) which provides a common transport layer and message set for unmanned vehicles and sensors. This protocol is mandated for all unmanned systems developed for the Future Combat Systems (FCS) program and the OSD Joint Robotics Program. Though JAUS has matured significantly over the last few years, it still lacks many of the features required for the FIRRE mission. JAUS has standardized messages for controlling core robot functions such as teleoperation and waypoint navigation; however it currently lacks a standardized way of adding payloads, such as unattended ground sensors and ground surveillance radars (though work is under way in this area by the JAUS working group). Typically, developers are required to implement “user-defined” JAUS messages (JAUS header with user-defined fields) to make up for gaps in the JAUS standard. Due to the aggressive nature of the FIRRE schedule, it was determined that the MRHA IDD provided a lower technical risk. The transition to JAUS will be undertaken in the next development spiral when the standard has reached a higher level of maturity.

In 2001, the MRHA protocol was extended to control the URBOT UGV. The MRHA software developed for MDARS requires a static list of all the resources in the system. For the URBOT project, an extension of the MRHA protocol was created called Small Robot Technology (SMART) that provided a mechanism for dynamic configuration. Instead of extending the existing MRHA software, the Multi-robot Operator Control Unit (MOCU) software was developed. This included the SMART software library that was used both inside MOCU and onboard the URBOT and to handle resource discovery and message transport and parsing.

Support for the iRobot *Aware* and JAUS protocols was later added to MOCU, prompting the development of protocol modules. At runtime, MOCU scans the current directory for DLLs that support the common protocol module interface. MOCU then loads these DLLs and uses them to translate protocol specific commands and data-structures to a common interface. This approach allows the MOCU core and user interfaces to treat all resources the same regardless of their native protocol, and third-party protocol modules to be added without having to re-compile the core MOCU software.

For FIRRE, a backwards-compatible SMART/MRHA protocol module was developed that combined the transport and message parsing of the SMART library with the features of the legacy MRHA software, and the new features required under FIRRE such as unattended ground sensors and ground surveillance radars payloads. When the SMART/MRHA protocol module was mature enough, all direct references to SMART were removed inside of MOCU, and the conversion to true protocol independence was completed. JBC2S makes use of these latest additions to the MOCU framework.

3.4 C2 Link Modules

One of the recent additions to JBC2S is the C2 Link module. This interface allows new modules to be written to connect with other military C2 systems such as Composeable Force Net (CFn), Enhanced Tactical Automated Security System (eTASS), Global Command and Control System Maritime (GCCS-M) or industry standards such as NMEA. This is JBC2S’s most flexible interface and allows for publishing and subscribing to manned and unmanned vehicle locations, routes, geometry, and tracks at varying refresh rates.

In the summer of 2006, FIRRE will demonstrate integration with the U.S. Army’s C-RAM program using the eTASS XML protocol developed originally by the U.S. Air Force. C-RAM consists of a system of overlapping, networked fire-finder radars that are capable of detecting and tracking rocket, mortar, and artillery launches, and provide warning to the affected areas of a forward operating base (FOB). This integration will allow the C-RAM eTASS system to see the location of FIRRE UGVs, UGSs, RSS towers, and intruders, and provide high level control and queuing. This will also allow JBC2S to see the point of origin and impact of any rocket, artillery, or mortar launches in the immediate area, and the locations of friendly or hostile units via eTASS’s interface with other U.S. Army C2 systems.

3.5 Map Modules

The look and feel of JBC2S is much improved over the MRHA through the display of raster graphics data in addition to vector graphics data. The use of raster images reveals much more detail about the environment and presents a modern, state-of-the-art user interface. Written to be modular and flexible, JBC2S defines a common mapping application interface.

One of the most common DoD mapping packages is the suite of ESRI products included in the Commercial Joint Mapping Toolkit (C/JMTK) program. The primary utilities of C/JMTK are ArcGIS Desktop and ArcGIS Engine Developer's Kit and Runtime (Figure 3). They natively support a broad range of geospatial data sources, including GeoTIFF, ADRG, Compressed ADRG (CADRG), Controlled Image Base (CIB), and WVS. These data sources can be seamlessly tiled together in either 2-D or 3-D viewing modes. The suite also provides many tools for analyzing geospatial data and converting from one format to another. A map module was written to embed this toolkit in JBC2S using the ArcGIS Engine Developer's Kit; however, some serious issues were encountered that have temporarily halted development. One of these issues is the incompatibility of the JBC2S architecture with the ArcGIS Engine architecture. In the JBC2S architecture, the core code defines how the application behaves and dictates how modules are intended to capture messages and events, and call back to the core code through callback functions. The ArcGIS Engine architecture is designed to support cartographical applications and is intended to be the core of the application that embeds the toolkit. The toolkit comes with its own toolbar, ArcMap (2-D), ArcGlobe (3-D), and ArcScene (3-D) components that work with each other. When integrated into JBC2S, these components are used individually and significant overhead code is needed to resolve the architecture incompatibilities. A second issue is the lack of library source code with the API that makes crashes in the library difficult to analyze and debug. Perhaps the most serious problem is that the recommended approach to drawing dynamic lines and symbols on the map results in slow, flashing graphics. Ultimately, it was the slow performance of the toolkit embedded in JBC2S that halted development. Efforts continue for the integration of the toolkit in other ways. For example, the ArcGIS Desktop application is being used to convert and combine different map formats to create maps for use by other JBC2S map modules.

As an alternative to C/JMTK, the popular and freely available Google Earth (formerly known as Keyhole) is being evaluated. Integrating Google Earth into JBC2S creates it own set of complications that are almost opposite of those encountered with C/JMTK. Through its XML-based API, Google Earth excels at drawing dynamic symbols and graphics on top of the map; however, it is not designed to be embedded inside of other applications, and the API is essentially making it difficult to integrate into JBC2S. Techniques such as window message hooking and other advanced windows "hacks" will need to be employed, which is highly undesirable. Another issue is the reliance on internet based data, which is almost never available in military command and control systems. This can likely be overcome by using higher end products such as the Fusion Server and Enterprise Client. Efforts are on-going to integrate Google Earth into JBC2S (Figure 4).

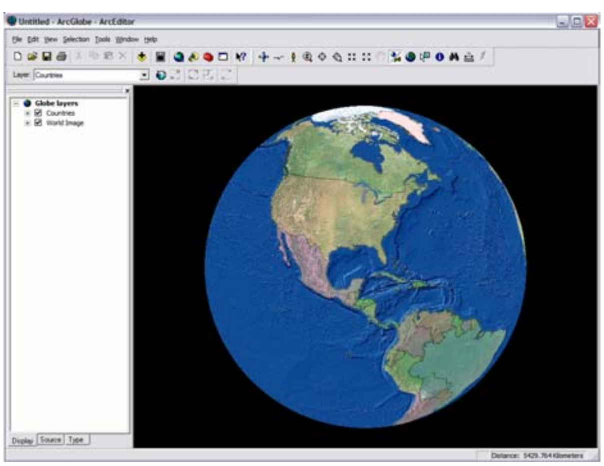

Figure 3: C/JMTK ArcGlobe.

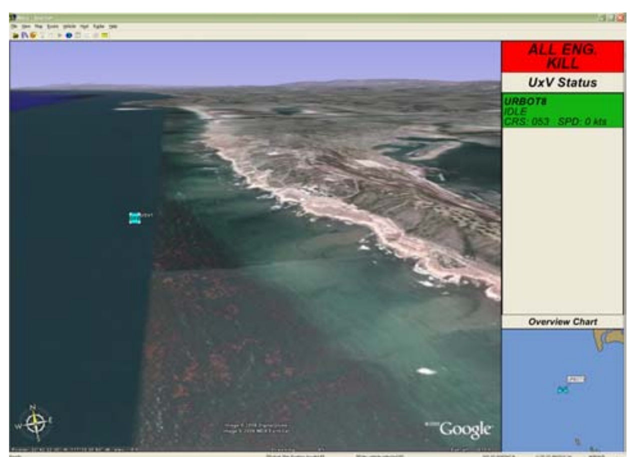

Figure 4: Google Earth inside MOCU.

Currently, JBC2S primarily uses map modules that are developed in-house, which handle 2-D display of maps in raster and vector formats. This approach supports a limited set of popular data formats and is extended as needed to support new data formats. These map modules use efficient techniques that allow for smooth graphic transitions during zoom in/out and panning, and keep up with real-time events common to the robotics environment; Valuable development time, however, is being consumed to make up for the lack of a good commercial package that meets these needs.

3.6 Control Methodology

In order to simplify the user interface, JBC2S operates under a very simple rule set. The system is either in Monitor Mode, in which the operator observes and monitors the status of the unmanned vehicles and sensors (known collectively as resources), or the operator is in Direct Control of a single resource. For example, a resource may have eight cameras, two radars, and four lights, but only a single camera, radar, and light is controllable at any given time. Multiple cameras can be viewed simultaneously, but the operator cannot pan two of them at the same time. A joystick button or dialog button can be configured to cycle between the various payloads. This paradigm reduces the complexity of the software and simplifies the user interface presented.

One could argue that it would be useful to allow control of multiple unmanned vehicles simultaneously. Many modern real-time strategy video games allow the user to drag a box around a group of units and send them to a location on the map or select an enemy unit to engage; however, current unmanned vehicle technology does not possess this level of autonomy. As the autonomy of unmanned vehicles increases, the methodology used in unmanned vehicle control software will need to continually evolve.

4. UGV INTEGRATION

4.1 Vehicle Status

The FIRRE UGV, developed by Northrup Grumman/Remotec, is a highly mobile tracked vehicle capable of off-road operation (Figure 5). The UGV has an integrated differential GPS navigation system that allows for high accuracy waypoint navigation and an obstacle detection system consisting of a SICK LIDAR mounted on the front of the UGV and six MA-Com radars mounted all around the vehicle to provide 360-degree coverage. This allows the vehicle to automatically stop for obstacles in its path during both waypoint navigation and manual teleoperation. The UGV has eight cameras: a front color driving camera, a rear color driving camera, four wide-angle black and white cameras, and the *SeaFLIR* stabilized imager with a combination FLIR and daylight camera. The vehicle also has a speaker and microphone to allow the operator to interrogate an intruder. To provide the ability to detect personnel and vehicles, the UGV is equipped with an *AN/PPS-5D* ground surveillance radar. The *AN/PPS-5D* can only be used when the vehicle is stationary, so it is automatically lowered into a protective cradle before the UGV is allowed to move. Under normal operating conditions, the UGV will be automatically dispatched according to a schedule established by the company commander. The UGVs will be put on patrol, sent to pre-programmed points of interest, and commanded to perform security detection scans of areas of interest. A variety of actions can be performed along paths as the UGV moves between points of interest such as camera movement, intruder detection scanning, and pre-recorded audio playback. If the UGV detects a potential target when performing a security scan, the operator will be automatically notified, wherein the operator will be able to assess the nature of the target by: 1) manually aiming the radar at the potential target to collect additional contact data; 2) listening to audio from the radar,; and 3) by visual means using the *SeaFLIR.*

Figure 5: FIRRE UGV.

The operator can stop the UGV when it is patrolling on its own to take manual control. The UGV will operate in a semi-autonomous mode when sent to a point of interest by the operator. If the UGV senses an obstacle in its path, it will stop and request assistance from the operator before proceeding. At this point in development, the UGV does not attempt to go around an obstacle on its own. The operator has to manually drive the UGV around the obstacle, and then resume the UGV on its path. When the UGV moves near or through areas such as intersections, cross walks, railroad tracks, or other potentially dangerous areas (from a personnel safety perspective), the UGV may ask the operator for clearance before proceeding through the area.

The operator can listen to audio from the UGV and generate pre-programmed sounds at the UGV, as well as speak through the UGV to personnel near the vehicle. The operator can manually operate the GSR when the UGV is stopped. The GSR is stowed in a safe position while the UGV is in motion. The operator can manually operate the *SeaFLIR* at all times when the UGV is powered on.

If the UGV senses that it is low on fuel, it will be automatically sent to a predefined re-fueling location and automatically powered down. If a potential target is detected by a Remote Sensor Station (either the ground surveillance radar or the unattended ground sensors), the operator is automatically notified and a UGV is automatically dispatched to a point near the detection for further assessment. More than one UGV can be operational at a time.

Figure 6: FIRRE UGV control in JBC2S.

The UGV provides a wide range of telemetry data back to JBC2S via the MRHA IDD protocol. The most important message in the MRHA IDD is the *Platform Get Status* that is sent to resources several times a second. Resources must send back a response message that contains their location, heading, operational mode, and other platform-specific information. The UGV provides telemetry data such as engine speed, engine temperature, hydraulic pressure, hydraulic temperature, track speed, fuel level, battery voltage, and obstacle detection data (Figure 6). It also provides the pan/tilt positions of the *SeaFLIR* imager and the *AN/PPS-5D* radar. JBC2S uses pan/tilt information to display coverage areas for these sensors on the map. The *Platform Get Status* response includes a number of flags such as GPS failure, emergency halt, low-battery warning, tamper alarm, and diagnostic failure. If the diagnostic failure flag is set, JBC2S queries the UGV for a detailed list of failures. The resource responds with a list of subsystems that have failed. The subsystems are identified by numbers that correspond to entries in a JBC2S configuration file. This file maps a subsystem number to a textual description, which provides a generic mechanism for reporting platform/manufacturer-specific failures to the operator.

4.2 Vehicle Control

In JBC2S, the control of a robot is broken into five categories based on the robot's level of autonomy: teleoperation, vector driving, waypoint navigation, static path planning, and dynamic path planning. The FIRRE UGV currently supports all of these levels of control except for dynamic path planning.

4.2.1 Teleoperation and Vector Driving

Teleoperation is actually broken into two types that are usually transparent to the user. In manual teleoperation, the user has complete control over the throttle and steering of the vehicle, normally via a joystick or handheld controller. In reflexive teleoperation, the user still controls the throttle and steering, but the robot's object detection and avoidance system attempts to keep the user from running into obstacles [5]. If a robot supports reflexive teleoperation, then it is likely that this will be the only type of teleoperation available to the user for safety reasons. To provide responsive teleoperation, JBC2S normally sends commands from the joystick at a 20-Hz rate. Teleoperation also requires low latency video, which the *DTC Palladium* video transmitter provides. Typical 802.11-based systems, which use compressed video, may have a second or more of latency making teleoperation very difficult for the operator.

Vector driving, used mainly with USVs or UAVs allows the operator to specify the desired heading and speed without having to provide joystick controls. It is effectively waypoint navigation with a single waypoint that the robot can never reach.

4.2.2 Waypoint Navigation and Path Planning

Waypoint navigation consists of the user drawing a series of waypoints on a georeferenced map, or manually entering coordinates using a keyboard (Figure 7). Each waypoint has parameters such as the desired speed, lane width (how far the robot can deviate from the centerline to circumnavigate obstacles), the capture radius (how close the robot needs to be to the waypoint to consider itself at the waypoint), and actions to perform at the waypoint (halt, slew a camera, etc). Static path planning consists of a series of pre-surveyed nodes and routes between the nodes. The user selects a node and the system automatically plans a path from the unmanned vehicle's current position to the selected node along the pre-surveyed routes (Figure 8). Dynamic path planning is where the operator selects a goal point and the robot plans the best route to reach that point. This assumes a very high level of autonomy on the part of the unmanned vehicle. The MRHA IDD does not define a path language that all resources are required to use. It instead provides a generic download mechanism that allows robot-specific path programs to be downloaded to a resource. For FIRRE's UGV, a path language was developed that closely matches the JAUS waypoint message while adding additional capabilities. The overall structure of the language is very simple (Figure 9).

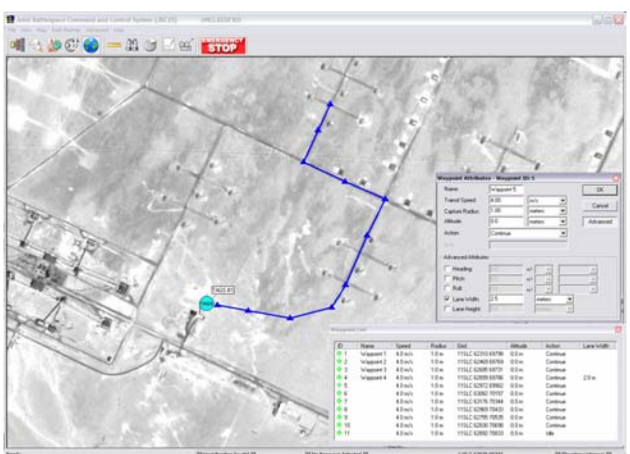

Figure 7: JBC2S manual waypoint navigation.

Figure 8: JBC2S static path planning.

Field #	Name	Type	Units	Interpretation
1	Number of Waypoints	Unsigned Short	N/A	Number of waypoints in this path (n-1)
2	Waypoint 0	Waypoint Structure	N/A	Waypoint 0 Data Structure
3	Waypoint 1	Waypoint Structure	N/A	Waypoint 1 Data Structure
n	Waypoint n	Waypoint Structure	N/A	Waypoint n Data Structure

Figure 9: UGV waypoint language.

Each waypoint structure (Figure 10) contains the location of the waypoint in geodetic coordinates, roll, pitch, and yaw at this waypoint, the desired speed along the path to this waypoint, and other tolerances. It also contains lane width and height fields that specify how far the vehicle can deviate from the centerline to circumnavigate around obstacles. The last field is the action script which is the most powerful part of FIRRE's UGV path language (Figure 11).

Field #	Name	Description
1	Presence Vector	Flags to indicate the presence of the optional fields in this structure
2	Waypoint Number	Waypoint Identifier
3	Latitude	Latitude of Waypoint Goal
4	Longitude	Longitude of Waypoint Goal
5	Elevation	Elevation of Waypoint Goal
6	ϕ (Roll)	Desired Roll at Waypoint Goal
7	θ (Pitch)	Desired Pitch at Waypoint Goal
8	ψ (Yaw)	Desired Yaw at Waypoint Goal
9	Speed	Desired Speed between Waypoints
10	Capture Radius	Effective Size of the Waypoint Goal
11	Roll Tolerance at Goal	Roll Accuracy Desired at Waypoint Goal
12	Pitch Tolerance at Goal	Pitch Accuracy Desired at Waypoint Goal
13	Yaw Tolerance at Goal	Yaw Accuracy Desired at Waypoint Goal
14	Lane Width	Deviation allowed in the horizontal plane along this path segment
15	Lane Height	Deviation allowed in the vertical plane along this path segment
16	Action Script	Scripted actions to perform once platform has reached waypoint goal.

Figure 10: UGV waypoint structure.

Function Name	Description
PAUSE	Pause platform (blocking)
HALT	Halt the platform
OFFLINE	Put platform offline
SENTRY	Start/Stop Sentry Mode
CAMERASCAN	Perform area scan with camera
CAMERAMOVE	Move camera to specified pose
CAMERASELECT	Select a camera video stream for transmission
SOUNDHORN	Sound the horn
PLAYSOUND	Play a sound on the platform
LIGHTS	Turn on/off the platform's lights
WAITCLEARANCE	Wait for operator clearance to proceed
RESTART	Restart Path Program Execution

Figure 11: UGV action script functions.

Action scripts are a series of ASCII text commands that allow for scripted actions when the UGV reaches a waypoint. The syntax of a script is modeled after C/C++ and consists of functions with parameters and terminating semi colons. The available functions consist of mode changes, camera movement, playing of sounds, and controlling lights. The WAITCLEARANCE function forces the UGV to request clearance from the operator before proceeding with the script. This can be used at intersections to allow the operator to verify that it is safe to proceed. The RESTART function causes the UGV to restart this path program from the beginning to allow for looping patrols. Here is an example of an action script:

```
SENTRY(ON);                       // Enter Sentry mode
CAMERASCAN(ON,1,90,180);          // Camera area scan
PAUSE(120);                       // Pause for 120 seconds
SENTRY(OFF);                      // Return to Idle mode
WAITCLEARANCE();                  // Wait for operator clearance
```

4.2.3 Automated Path Planning

Like the legacy MRHA software developed for MDARS, JBC2S supports automated path planning but uses a more flexible XML-based path database. This database consists of pre-defined nodes and interconnecting routes. When the operator selects a destination node for a robot, a recursive depth-first search algorithm is used to find the shortest route using pre-programmed routes. For fixed installations, this capability is required to allow for automated patrols of

perimeter roads, bunkers, and facilities. The FIRRE combat developers have many times expressed an interest in being able to plan routes off-road to allow for quicker and more dynamic reactions to events, and to take full advantage of the UGV's mobility. Currently, off-road path planning is possible, but only along known surveyed routes. The next step is to allow the operator to plan routes through unsurveyed areas using a combination of terrain data and obstacle-detection sensors and avoidance algorithms, but this is beyond the scope of FIRRE's initial spiral development.

5. PAYLOAD INTEGRATION

5.1 Cameras

FIRRE employs several cameras, each with different capabilities and features. FIRRE's UGV has a number of fixed cameras for situational awareness around the vehicle as well as the *SeaFLIR II* (Figure 13), which is a stabilized FLIR and daylight pan/tilt/zoom camera with an integrated visual tracker and laser pointer. FIRRE's RSS [3] has a *DI-5000* FLIR and daylight pan/tilt/zoom camera (Figure 14) that allows for blending between infrared and daylight images (known as fading).

Figure 13: SeaFLIR II FLIR.

Figure 14: DI-5000 FLIR.

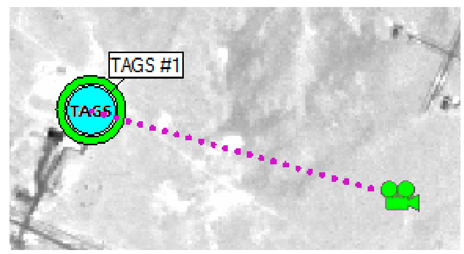

Figure 15: Slew-to-Cue tool.

If the video is available in digital form (e.g. streaming MPEG-4) it can be displayed inside JBC2S either in a fixed or floating video window. JBC2S currently supports both the *Video Bridge 6000/8000* and the *Axis Video Server* CODECs via a generic DLL interface, allowing future CODECs to be added without any changes to the core JBC2S software.
JBC2S allows cameras to be controlled via a control dialog, a joystick, or via the Slew-to-Cue tool (Figure 15). The control dialog features pan/tilt/zoom controls as well as focus, gain, and fader controls. Joystick commands are user defined and can be easily customized for different joysticks and applications. The Slew-to-Cue tool allows the operator to aim a camera at a georeferenced point using a map. Coverage areas of cameras can also be displayed on the map, allowing the user to better visualize how the video relates to real world coordinates.

5.2 Ground Surveillance Radar

To provide long-range intruder detection, *AN/PPS-5D* ground surveillance radars (GSR) (Figure 16) are integrated onto the RSS towers and the UGV. The *AN/PPS-5D* is a Doppler radar capable of detecting personnel and vehicles at 10-20 KM; however, terrain obstructions can significantly decrease the performance. The *AN/PPS-5D* can be manually steered or set to perform an area scan up to 359 degrees in width. The *AN/PPS-5D* is normally controlled and monitored by co-located trained personnel and was not designed to be remotely operated. This has resulted in some integration challenges that are still being researched. Perhaps the most serious issue is that the *AN/PPS-5D's* pan positioner cannot determine absolute heading and initializes to 0 degrees heading on power-up. A proximity sensor system has been developed to allow for automated calibration, which is necessary to ensure that radar data can accurately be displayed on a georeferenced map inside of JBC2S. Another issue is that the radar's tilt is not remotely controllable, which can be problematic in anything but the flattest terrain.

The radar reports contacts as uncorrelated points with a range, bearing, amplitude, and Doppler velocity (Figure 17). The lack of an integrated tracker greatly increases the burden on the operator. The radar has Doppler audio that is required to accurately determine if contacts are noise, personnel, or vehicles. More development is needed to improve the utility of this radar for automated fixed-site security applications such as FIRRE.

Figure 16: AN/PPS-5D Ground Surveillance

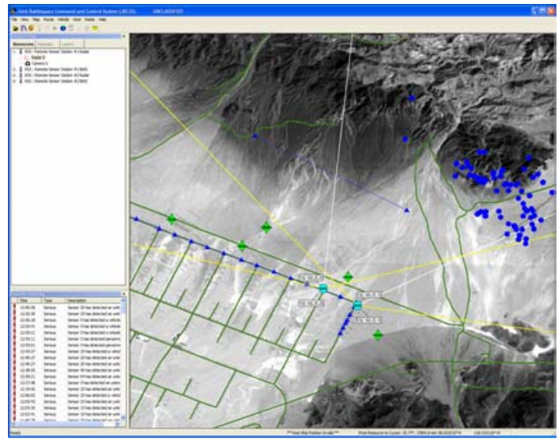

Figure 17: JBC2S Controlling PPS-5D.

5.3 Unattended Ground Sensors

The Battlefield Anti-Intrusion System (BAIS) (Figure 18) is used to augment the wide-area coverage of the *AN/PPS-5D* radar. These combination seismic and acoustic sensors allow for monitoring likely avenues of approach such as roads, wadis, heavy vegetation, etc, that don not lend themselves to other sensors. The BAIS is the latest generation of the Remote Battlefield Sensor System (REMBASS) that has been around for over 20 years. The BAIS sensors can detect personnel at up to 50 meters and vehicles at 250-350 meters. The sensors automatically classify detections as personnel, vehicle, wheeled vehicle, tracked vehicle, or unknown. Messages from emplaced sensors are received using a handheld monitor that communicates with a PC using an RS-232 interface.

For FIRRE, these handheld monitors are integrated into the RSS and C2 Station to allow BAIS detection and status messages to be fed into JBC2S. The locations of sensors are displayed on the map using MIL-STD-2525B symbols. When a sensor reports a detection, JBC2S flashes a red icon on top of the sensor symbol indicating the type of event, an audio notification is played, and the event is logged for later review and analysis (Figure 19).

Figure 18: Battlefield Anti-Intrusion System (BAIS).

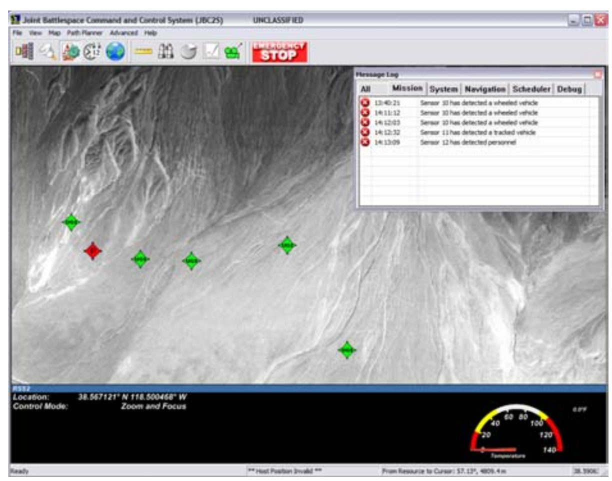

Figure 19: JBC2S displaying BAIS event.

5.4 Lessons Learned

With each new robot or payload comes its own set of challenges. The most important lesson learned during payload integration is that all payloads (cameras, sensors, radars, weapons, etc) share commonalities that need to be exploited to minimize software development effort. A new payload architecture for JBC2S is being developed that will generalize both the interface with payloads and the way that the controls for payloads are presented to the user.

6. FUTURE EFFORTS

In the near term, JBC2S will be integrated with the MDARS platform for backwards compatibility as well as to provide an alternative vehicle platform. A non-lethal payload utilizing the Long Range Acoustic Device (LRAD), a high-power direction speaker system, is being developed for the FIRRE UGV to provide a response capability. A software-based video distribution server is being developed to provide the ability to stream multiple live video feeds from resources across a LAN or the internet.

In the next spiral of development for FIRRE, other payloads will be considered for integration such as wide-area infrared sensors and unattended lethal/non-lethal weapon systems such as the Common Remotely Operated Weapons System (CROWS), MATRIX, and the Networked Remotely Operated Weapons System (NROWS). Additional plans include integration of FIRRE with a multitude of other unmanned systems including USVs, UAVs, and other UGSs. SSC SD has already demonstrated the simultaneous command-and-control of multiple UGVs, USVs, and UAVs using MOCU [4]. FIRRE will push the readiness level of the unmanned systems and integrate control of these systems into JBC2S.

REFERENCES

1. D. Powell, G.A. Gilbreath, *Multi-robot Operator Control Unit (MOCU)*, SPIE Proc. 6230-67, Orlando, FL, 2006.
2. R.T. Laird, T.A. Kramer, J.R. Cruickshanks, K.M. Curd, K.M. Thomas, J.C. Moneyhun, *FIRRE Command and Control Station (C2)*, SPIE Proc. 6230-85, Orlando, FL, 2006.
3. J.R. Cruickshanks, E.L. Wickstrand, T.A. Kramer, R.T. Laird, C.W. Gardner, *FIRRE Remote Sensor Station (RSS)*, SPIE Proc 6230-100, Orlando, FL, 2006.
4. K.M. Curd, H.R. Everett, *Center Conducts Collaborative UGV/UAV/USV Demonstration*, Space and Naval Warefare Systems Center Robotics Update, Vol. 5, Nov 4, San Diego, CA, Fall 2005.
5. Laird, R.T. and H.R. Everett, "Reflexive Teleoperated Control," Association For Unmanned Vehicle Systems, 17th Annual Technical Symposium and Exhibition (AUVS '90), Dayton, OH, pp. 280-292, July-August, 1990